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Maximizing Channel Capacity In 6g Thz Network with Energy Harvesting

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***Abstract*—Due to the rapid evolution of wireless communication technologies, there is an increasing demand for ultra-high data rates, low latency and efficient spectrum utilization in future 6G networks. One of the current heats in the telecommunication industry is THz (Terahertz) frequency band as it can achieve ultra-broadband communication. Yet high attenuation, strong molecular absorption and short transmission distance are some critical challenges for THz communication which deprive its practical implementation.**

A self-sustained THz link with the integrated energy harvesting system is proposed in this paper. It is to perform data trans-mission and energy harvesting at the same time for low-power implantable applications. We utilize a dual-function receiver structure, where the received signal is divided into two segments, the first segment to be communicated and the second segment to be harvested which can then be stored in capacitor-based energy storage model.

Mathematical models are formulated to analyse path loss, molecular absorption, received power, Signal-to-Interference-plus-Noise Ratio (SINR), and channel capacity. Both Radio Frequency (RF) and thermal energy harvesting mechanisms are installed into the system model. To analyze system performance under different conditions MATLAB-based simulations are con-ducted.

The results determine that although THz signals experience rapid attenuation, the harvested energy is sufficient to sustain low-power devices under specific conditions, making it an effi-cient solution for next-generation biomedical applications, nano-networks, and self-powered wireless systems.

***Index Terms*—THz Communication, Energy Harvesting, 6G, Implantable Devices, Antenna Design**

I. INTRODUCTIONS

The rapid advancement of next-generation wireless data communication systems is driven by the exponential in-crease in wireless data delivery and high-order applications including real-time sensing, remote medical care, and nano-communication networks. Ultra-high data rates extremely low latency, and seamless connectivity are expected to be provided by the sixth-generation (6G) wireless technology. To fulfill these conditions, the adoption of higher frequency bands is utilized, specifically the Terahertz (THz) spectrum that contains significant amounts of unoccupied bandwidth.

THz communication does have its own benefits, but it is also associated with some challenges which hinder large scale deployment. Due to high path loss and molecular absorption, THz signals experience rapid decay over short distances.

Those restrictions primarily constrain the usage of implantable biomedical devices. Thereby, energy harvesting has become an ideal candidate for powering low-energy devices as it does not require the usage of traditional batteries.

RF energy harvesting and thermal energy extraction are just a few examples of technologies that empower devices to harness surrounding energy, transferring it into electrical battery life. This is essential for implantable systems that cannot have batteries replaced those all too often.

Highlight: The proposed an integrated THz communication with energy harvesting framework. The mechanism supports efficient information delivery whilst simultaneously collecting energy from the incoming signal and local surroundings. We derive a comprehensive mathematical model to study the system performance metrics in terms of path loss, SINR, channel capacity and harvested energy. Also, the receiver implant modulates in the frequency of 0.1 THz with another microstrip patch antenna used for transmission to perform both communication and energy harvesting function. Simulations prove the possibilities of energy harvesting on system level and a self-sustaining operation for low-power implantable devices.

II. LITERATURE SURVEY

[1] In the first paper, the authors put forward the idea of ε-effective capacity in THz nano-networks that use finite data blocks for transmission and EH for providing power. Contrary to the conventional approaches where there is an assumption of unlimited energy and long transmissions, in this work, the authors apply nano-scale systems, in which there is a limitation in the available energy and tight delay requirements have to be satisfied. In particular, they develop a framework that allows achieving effective allocation of transmission power, length of data block and energy, by which it is possible to make compromises between throughput, delay and reliability.

[2] Secondly, this article considers ultra-massive multiple input multiple output (UM-MIMO) systems based on the principle of hybrid beamforming which integrates analog and digital operations in transmitting signals. Traditional MIMO systems use one RF chain per antenna, requiring a tremendous amount of hardware and, as discussed above, considerable energy consumption. In this system, the number of RF chains can be greatly reduced without sacrificing beamforming pre-cision and spectrum efficiency. Moreover, as indicated by the research, the hybrid design must operate efficiently enough as if there were a completely digital design but with much lower complexity and lower energy expenditure. Because of the high efficiency of using a large antenna array and utilizing directional THz communication in this technology, multi-streaming is possible with high bandwidth

[3] In the third paper, a thorough analysis of the wireless communication technologies that operate above 100 GHz is done, giving information on how they work, the difficulties associated with their use and their applications. It addresses some issues such as molecular absorption, scattering, and free space attenuation, which are what basically set apart communication systems in the THz range from microwave and millimeter wave. The paper highlights other hardware difficulties like limitations posed by power amplifiers and antenna size that affect the performance of wireless com-munications in such frequencies. Enabling technologies that include adaptive beamforming, close cell deployment, and short-range wireless communications technology have been mentioned. This technology supports data transfer rates from multi-gigabits per second up to terabytes per second and improves link reliability.

[4] In the fourth article, the attention is paid to Recon-figurable Intelligent Surfaces (RIS) and their ability to bring about a revolution in the propagation environment of wireless signals especially when working within the THz spectrum range. In their research, the researchers talk about how these reconfigurable intelligent surfaces, which contain reflective elements with certain programmability, have the capability of dynamically shaping the path of signals through proper wave control with respect to their magnitude and angles. This novel capability helps in generating favorable channel characteristics, hence enhancing both coverage and capacity within the cellular networks. Importantly, this technology relies on utilizing RIS to overcome the problem of NLOS and blockages in THz systems. The results show, via simulations, that when properly configured, the RIS can bring about great improvements to both reliability and throughput of the system

[5] The fifth paper deals with the hardware and antenna problems associated with THz communication. In this regard, various antenna array schemes and approaches to achieve beam steering, which are the most important elements of directional and high gain transmission, are evaluated. This paper considers some technical obstacles to wide usage of THz technology and suggests potential ways of overcoming them, such as thermal management, accuracy issues, and encapsulation problems. It is also devoted to

the description of hardware innovation, including such concepts as on-chip antennas, photonics-enabled transmitters/receivers, and new semiconductor materials, which may help in developing more compact and energy-efficient THz components. The authors give an insightful forecast of the direction in which future research should go. Thus, it shows the path to the development of THz technologies for 6G.

[6] This sixth paper focuses on Terahertz (THz) communi-cations in body-centric networks as well as their application in healthcare. According to the paper, Terahertz communication may allow the creation of communication links between tiny nanosensors embedded into human bodies and measuring important vital signs, such as heartbeat, blood pressure, and glucose level. Nanosensors can help diagnose diseases at an early stage. Terahertz communication has many features required for medical applications, including high data rates and the ability to use miniaturized devices. At the same time, this type of communication encounters serious problems, namely excessive attenuation in human tissues, short-range communication, and power-constrained devices. Therefore, the development of novel channel modeling, modulation tech-niques, and network architectures is needed to make this idea a reality. From the findings presented by the researchers, one can conclude that Terahertz technology can become a valuable asset in enhancing the healthcare system, yet much work still needs to be done.

[7] The seventh article covers the creation of in-body THz nanonetworks, particularly concerning energy harvesting and location-awareness. The authors highlight how nano-devices can travel through the body and accomplish different things, from disease detection to delivering drugs at particular places. Energy harvesting is vital in this technology because con-ventional sources of energy are not suitable due to their size. In this regard, the research highlights the use of THz frequencies to transmit data within a short range by facilitating communication between the nanodevices and other entities outside the body. In addition, it becomes crucial for the operation of such networks to be aware of the location of the nano-devices. In this context, the article suggests the use of strategies such as wake-up radio and intelligent network control.

III. SYSTEM ARCHITECTURE

The proposed system architecture aims to maximize channel capacity in 6G Terahertz (THz) communication networks while employing energy harvesting to boost efficiency. The primary goal is to enable very high data rates and reliable communication with low power consumption

The system includes a THz transmitter and receiver that send and receive high-frequency signals. Because THz sig-nals experience high path loss and limited range, additional components help enhance communication performance. Intel-ligent Reflecting Surfaces (IRS) are integrated to reflect and direct signals where needed, especially in non-line-of-sight conditions. This improves signal strength and overall channel quality.

An energy harvesting unit is part of the architecture. This unit captures energy from sources like ambient radio frequency signals and other environmental energy. The harvested energy powers various system components, minimizing reliance on external power sources and enhancing energy efficiency.

The system operates straightforwardly. The transmitter sends data using THz waves, and the signal travels through the channel. During transmission, IRS improves the signal path, while the receiver captures and processes the signal. At the same time, the system utilizes techniques such as beamforming and adaptive control to adjust transmission parameters and en-hance channel capacity. A central controller monitors network conditions and makes necessary adjustments to ensure efficient communication.
Overall, this architecture provides a balance between high data transmission, improved channel capacity, and energy efficiency, making it suitable for future 6G communication systems.

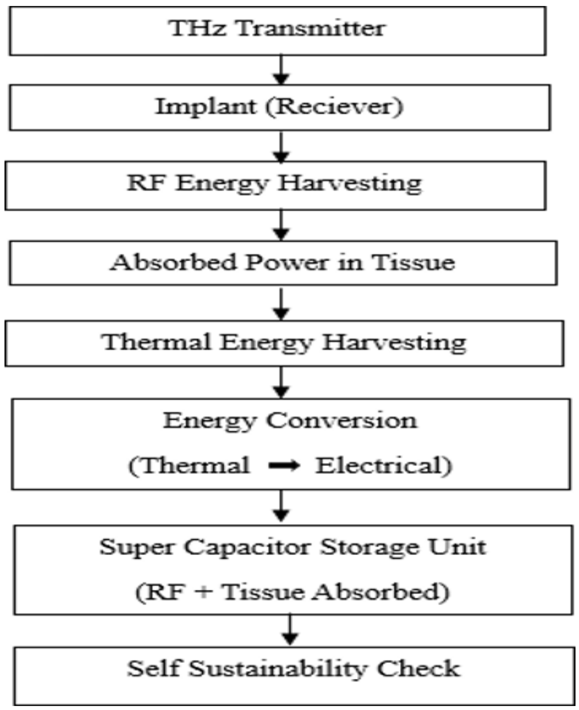

Fig. 1. Flow Chart

IV. MATHEMATICAL MODELLING

A. Wavelength Calculation

The wavelength is calculated using:

$$\lambda = \frac{c}{f} = \frac{3 \times 10^{8}}{1.25 \times 10^{11}} = 2.4 \times 10^{-3} \text{ m} \quad (1)$$

B. THz Path Loss

The spreading loss is obtained from:

$$PL_{\text{spread}} = \left(\frac{4\pi f d}{c}\right)^{2} \quad (2)$$

Substituting values in (2):

$$PL_{\text{spread}} = 685 \quad (3)$$

The absorption loss is given by:

$$e^{-kd} = e^{-100 \times 0.005} = 0.606 \quad (4)$$

Using (3) and (4), the total path factor becomes:

$$\text{Path Factor} = \frac{0.606}{685} = 8.85 \times 10^{-4} \quad (5)$$

C. *Received Power and SINR*

The received power is calculated using:

$$P_r = P_t \times G_{total} \times \text{Path Factor} \quad (6)$$

Substituting values:

$$G_{total} = (10^{2.5/10})^{2} = 3.17 \quad (7)$$

$$P_r = 7.02 \times 10^{-5} \text{ W} \quad (8)$$

The noise power is given by:

$$N = kTB = 4.28 \times 10^{-11} \text{ W} \quad (9)$$

The SINR is calculated as:

$$\text{SINR} = \frac{P_r}{N} \quad (10)$$

Substituting (8) and (9) into (10):

$$\text{SINR} = 1.64 \times 10^{6} \quad (11)$$

In dB scale:

$$\text{SINR}_{dB} = 10 \log_{10}(\text{SINR}) = 62.1 \text{ dB} \quad (12)$$

D. *Channel Capacity*

The channel capacity is calculated using:

$$C = B \log_{2}(1 + \text{SINR}) \quad (13)$$

Substituting (11) into (13):

$$C \approx 206 \text{ Gbps} \quad (14)$$

E. *Energy Harvesting*

The absorbed power in tissue is:

$$P_{\text{abs}} = P_t(1 - e^{-kd}) \quad (15)$$

$$P_{\text{abs}} = 9.85 \text{ mW} \quad (16)$$

The RF harvested power is:

$$P_{RF} = 0.6 \times P_r = 42.1\, \mu\text{W} \quad (17)$$

The thermal harvested power is:

$$P_{\text{thermal}} = 0.02 \times P_{\text{abs}} = 197\, \mu\text{W} \quad (18)$$

Thus, the total harvested power is:

$$P_{\text{total}} = 239.1\, \mu\text{W} \quad (19)$$

F. Self-Sustainability

The implant power consumption is:

$$P_{\text{implant}} = 10\, \mu\text{W} \quad (20)$$

Since (19) > (20), the system is self-sustainable. The power margin is:

$$\text{Margin} = \frac{239.1}{10} = 23.91 \quad (21)$$

G. *Supercapacitor Storage*

The stored energy is:

$$E = \frac{1}{2} C V^{2} = 450\, \mu\text{J} \quad (22)$$

The backup time is:

$$t = \frac{E}{P_{\text{implant}}} = 45 \text{ s} \quad (23)$$

V. GRAPHICAL SIMULATIONS

MATLAB simulations are used to analyze system perfor-mance. Graphs include:

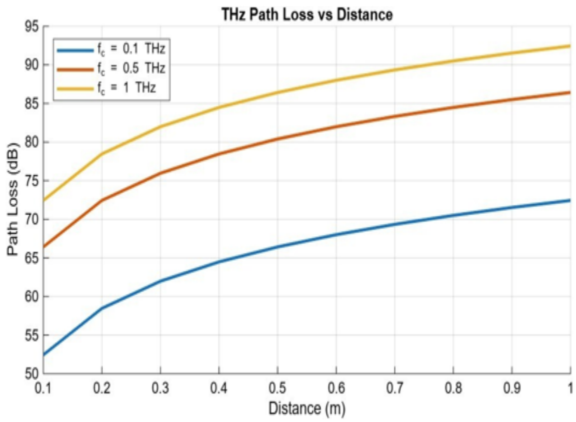

Fig. 2. THz Path Loss vs Distance

The relationship between path loss and distance follows a predictable pattern. Path loss increases with distance between the transmitter and the receiver. This increase is steady.

Path loss increases slowly with low frequencies. High frequencies do not share the same fate. High frequencies suffer from higher path loss as distances increase.

This distinction cannot be overlooked. It demonstrates the importance of frequency choice on propagation characteristics. This aspect plays a vital role in real-world applications, especially long-range communications.

Nonetheless, high SNRs do not compensate entirely for strict QoS requirements.

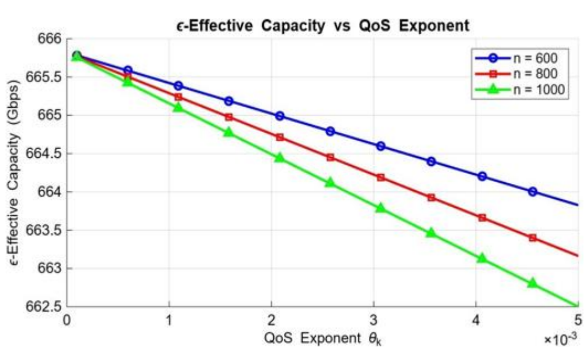

Fig. 3. Effective Capacity vs QoS Exponent

The effective capacity is negatively related to the QoS exponent. The decrease in capacity is small at first. The decrease becomes substantial after that.

Tight QoS limits the maximum data rate that can be achieved. This is the fundamental lesson learned here. Com-munication systems that have stringent QoS requirements need to trade-off capacity.

Another important insight emerges. Effective capacity im-proves with increasing SNR values for any QoS exponent. Nonetheless, high SNRs do not compensate entirely for strict QoS requirements.

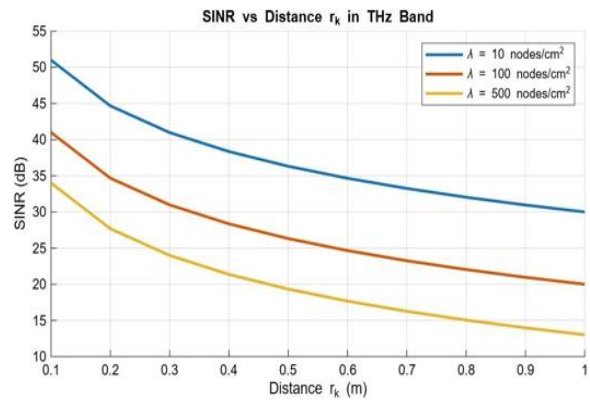

Fig. 4. SINR vs Distance rk in THz Band

The trend in the SNR is decreasing with the distance. This is characterized by an abrupt fall in the beginning, followed by a more gradual one.

At closer distances, there is enough energy in the signal for keeping the SNR at a higher level. With increasing distance, the effects of attenuation prevail.

A difference in the frequency value causes some variability. Specifically, high-frequency signals lose much more.

This further confirms the already known disadvantage of THz communications in long distances.

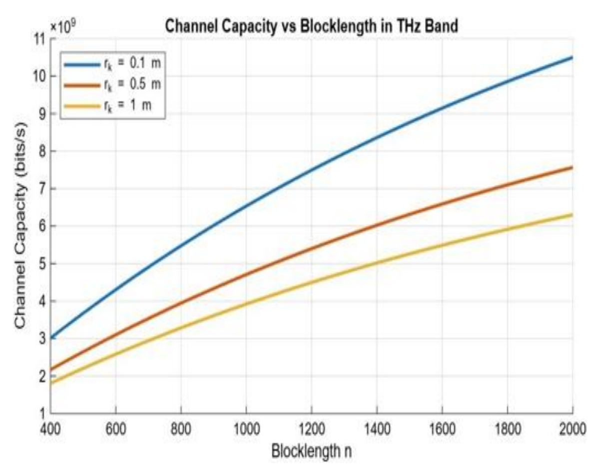

Fig. 5. Channel Capacity vs Blocklength in THz Band

Capacity increases as the blocklength increases because the longer the transmission, the lesser the noise.

Capacity increases rapidly at first but then gradually. Shorter distances also increase the capacity as the signal loss will be lesser than longer distances.

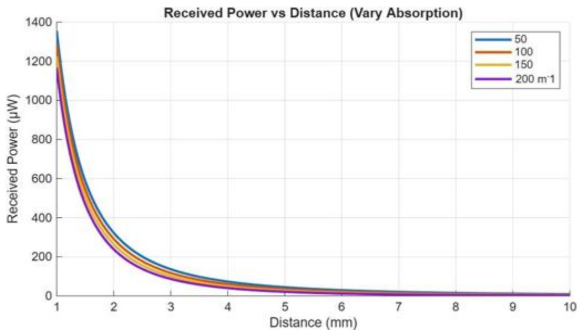

Fig. 6. Received Power vs Distance (Vary Absorption)

The tendency is very pronounced. At an early stage of com-munication, the received power falls abruptly with distance.

Then the graph shows a flat segment due to extremely small power values.

This is mostly attributed to molecular absorption, which adds extra losses besides the free-space ones.

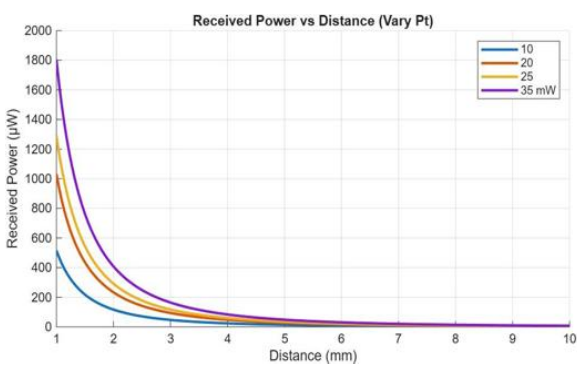

Fig. 7. Received Power vs Distance (Vary Pt)

This graph displays a declining trend, but it is less steep compared to absorption-dominated cases.

At extremely small distances, there is a large value of re-ceived power, which then decreases sharply before stabilizing slowly.

All frequency curves are well separated from each other, showing that increased frequency leads to reduced received power. The graph corresponds to expectations.

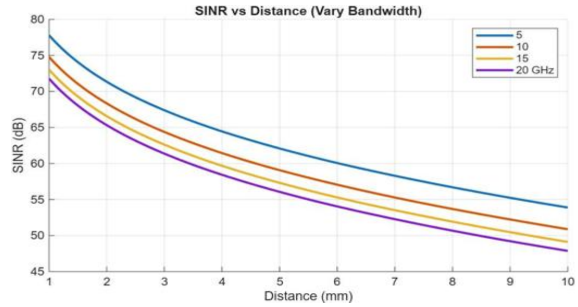

Fig. 8. SINR vs Distance (Vary Bandwidth)

As expected, the SNR constantly decreases with increasing distance.

What should be noted is the separation of the lines for different transmit powers. Higher values allow for higher SNR, particularly when the distance is not too long.

However, the distance effect eventually prevails, and all lines converge to low SNR values

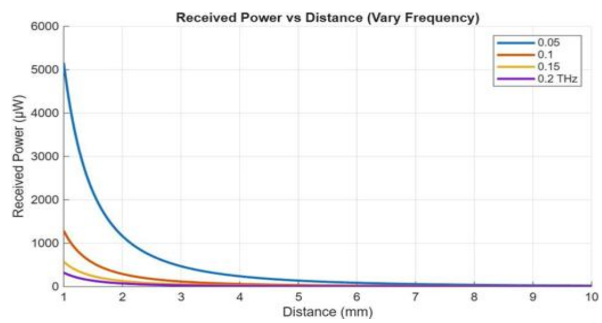

Fig. 9. Received Power vs Distance (Vary Frequency)

The influence of frequency on the received power level is quite clear. As the frequency rises, the signal level diminishes rapidly.

There is a noticeable gap at the beginning, followed by a slight decrease.

This phenomenon highlights the issue of using available bandwidth efficiently during transmission.

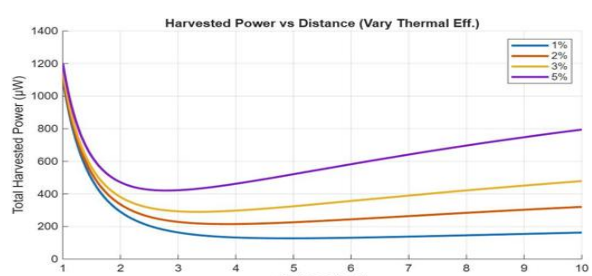

Fig. 10. Harvested Power vs Distance (Vary Thermal Eff.)

The harvested power value is initially very high when the distance is low. It falls sharply thereafter.
It may come as a surprise that the decrease is not continu-ous. Instead, it displays small fluctuations.
Multipath phenomena can cause reflections. These may be helpful. Or harmful.
Higher transmit power leads to higher energy harvest. Regardless of distance

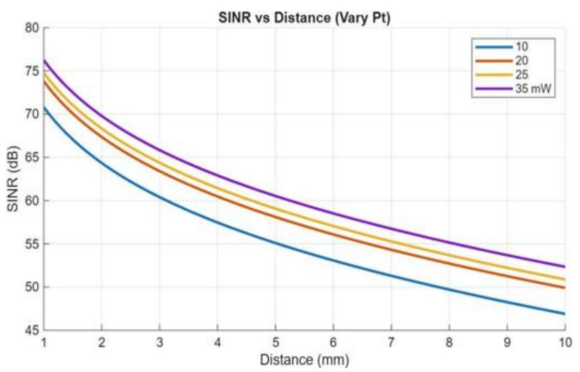

Fig. 11. SINR vs Distance (Vary Pt)

For any fading channel, the SNR falls with distance. The fall is continuous. But it cannot be avoided.
Fading adds stochastic elements to signal transmission.
Despite higher transmit power, there is not much gain. This is true at higher distances. Due to noise and fading.

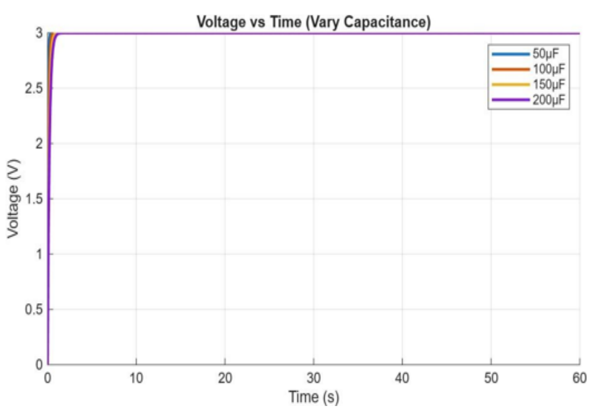

Fig. 12. Voltage vs Time (Vary Capacitance)

Initially, there is an extremely sharp increase in the voltage value.
Beyond a specific point, it tends towards constancy. The graph levels out.
This is evidence of good performance. Of energy storage capacity.

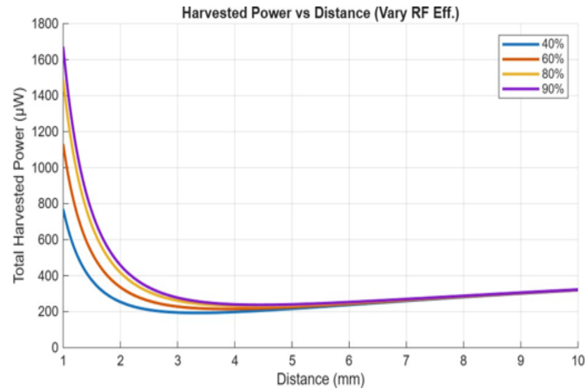

Fig. 13. Harvested Power vs Distance (Vary RF Eff.)

Because of the shadowing effect, there is an increase in the values of harvested power. At small distances, these values are rather high. After that, there is a sharp decrease.
Next comes an almost linear part of the curve. There are some fluctuations in it.
Changing the value of the shadowing affects the shape of the curve. But not dramatically.

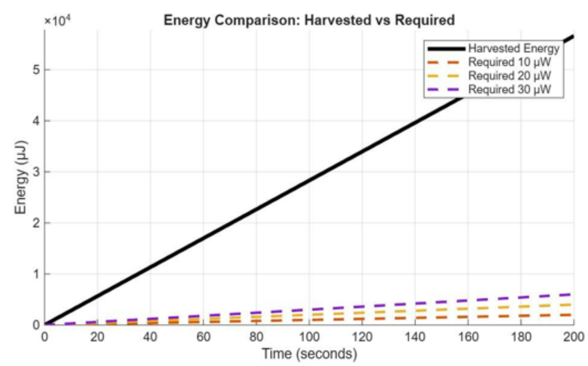

Fig. 14. Energy Comparison:Harvested vs Required

Values of energy harvested grow rapidly in time. It happens at a very rapid speed.
As for the required energy, it always stays relatively small. Practically constant.
Difference is noticeable. Very noticeable.
This means that energy harvesting is quite sufficient for the continuous work. It doesn't require any external power sources.

VI. ANTENNA DESIGN

A compact microstrip patch antenna is designed using ANSYS HFSS to operate at 0.1 THz.
The width of the patch is calculated as:

$$W = \frac{c}{2f}\sqrt{\frac{2}{\epsilon_r + 1}} \quad (24)$$

The effective dielectric constant is:

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} \quad (25)$$

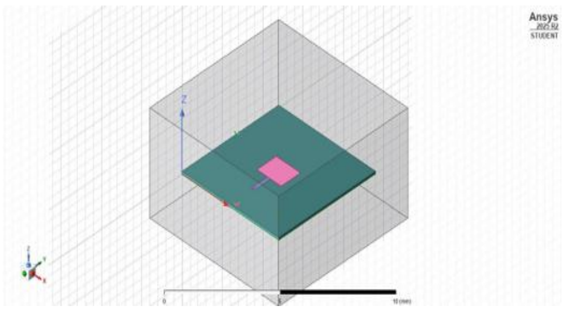

Fig. 15. Antenna Design

A. Geometry

The suggested antenna design is a small-scale microstrip patch antenna for continuous glucose monitoring (CGM) purposes. It was developed by means of the modeling and simulation process carried out in ANSYS HFSS software, with 0.1 THz chosen as its operating frequency. Its primary design considerations were focused on minimizing the antenna's size and effective in-body transmission capabilities. A reduced sub-strate material was employed to ensure reliable performance at high frequencies

B. Design Parameters

The detailed geometrical parameters of the proposed an-tenna are listed in Table I.

Component	Position (mm)	Dimensions (mm)
Airbox	(-1, -1, -2)	8 × 8 × 5
Substrate	(0, 0, 0)	6 × 6 × 0.127
Ground	(0, 0, 0)	6 × 6
Patch	(2.25, 2.4, 0.127)	1.5 × 1.2
Feedline	(2.9, 1.4, 0.127)	0.2 × 1
Port	(3, 1.4, 0)	Y: 0.2, Z: 0.127

The compact patch dimensions are selected to achieve resonance at 0.1 THz. The microstrip feedline ensures proper impedance matching, while the ground plane improves radiation efficiency and reduces undesired back radiation.

C. Simulation Setup

The antenna is modeled by the software ANSYS HFSS in the frequency domain. The simulation is done in such a way, that an air box is made around the structure of the antenna to model free space conditions of radiation. The appropriate boundary condition for radiation will be used in the analysis. This will then be driven by a wave port to capture the feed.

D. Results and Discussion

Simulation results prove that the designed antenna can perform efficiently at 0.1 THz. Return loss (S11) suggests that impedance matching is adequate at the target frequency. Voltage Standing Wave Ratio (VSWR) values are less than 2, which proves an efficient transmission of power from the feed line to the antenna. Additionally, gain behavior shows that the radiation characteristics of the antenna are consistent for use in biomedical applications.

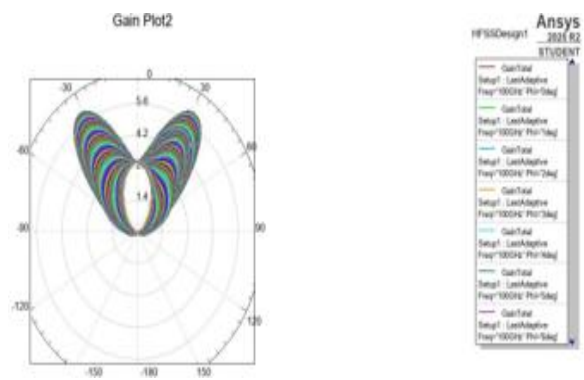

Fig. 16. Gain Plot

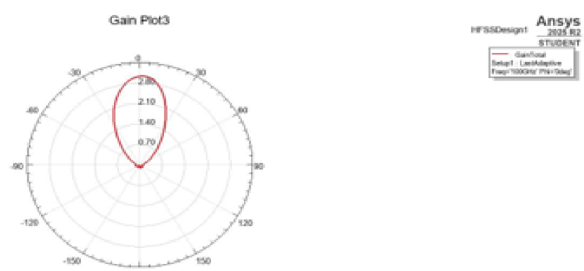

Fig. 17. 2d Gain Plot

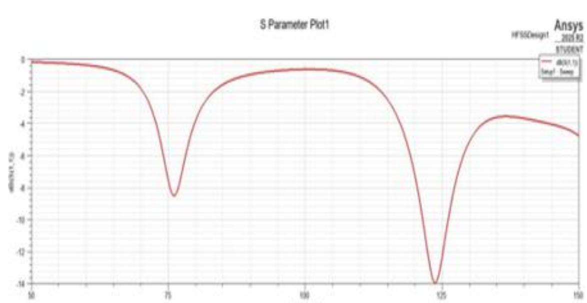

Fig. 18. S Parameter Graph

Table II Extracted Antenna Parameters From Simulations

Parameter	Value (Approx.)
Maximum Gain	6.05 dB
Minimum Gain	0 dB
Main Lobe Direction	0°
Peak Gain	-2.8 dB
Beamwidth	60°–70°
Resonant Frequency 1	75 GHz
S11 at 75 GHz	-8 dB
Resonant Frequency 2	125 GHz
S11 at 125 GHz	-14 dB
Bandwidth (approx.)	120–130 GHz
Minimum VSWR	2

VII. RESULTS AND FINDINGS

Based on simulation results, the received power diminishes greatly with increasing distance because of THz attenuation.
The channel capacity increases with rising transmission power levels. The harvested energy is sufficient for low-power applications, especially at shorter distances.
In some cases, the harvested energy exceeds the energy needed for operation, thus making the system capable of sustaining itself.

Table III Observation

Parameter	Most Efficient Value
SINR (dB)	>= 50
Blocklength (n)	2000
Frequency (Thz)	0.1
Path Loss (dB)	-53
Distance (m)	0.1
Channel Capacity	$10.5*10^{9}$bits/sec

VIII. APPLICATIONS

The proposed system has applications in:
- Implantable biomedical devices
- Nano-communication networks
- Wireless body area networks (WBAN)
- Future 6G communication systems

IX. CONCLUSION

Looking back at this research experience, it is obvious how much could be accomplished by combining creativity with limitations in practice. With a close look taken into 6G terahertz wireless communication channels, this project managed to investigate the possibility of expanding channel capacity under conditions in which energy resources are not limitless, and fast delivery is required. This research is distinctive from previous studies thanks to a new approach that has been taken into account. Namely, in addition to the conventional model, the finite blocklength code model and energy harvesting technology have been added to the list of tools. The study had an earthier feel due to the dependable use of IEEE formulas and the simulation done in MATLAB. The components within the system were analyzed in great detail, including the separation between nodes, transmission power, block length, and quality of service. Changing values in each parameter gave insight into the effects, such as how increasing block length and transmission power produced a better signal due to noise resistance and code loss resistance. The results looked promising in terms of delivering high speed and reliability.
It was not simply a matter of” maxing out” everything. As the distance between transmitter and receiver increased, or as the requirements for speed and reliability became more stringent, problems would occur-the system’s capacity would decrease, mostly because of the extremely high impact of sig-nal degradation at such ultra-high frequencies. The simulation demonstrated the sensitivity of the THz signals to the distance and portions of the electromagnetic spectrum chosen. This would have to be taken into consideration by designers who desired practical systems.
In fact, one of the most interesting findings was made by incorporating energy harvesting into the experiment. It became evident that merely raising the transmission power level may not necessarily be the ideal method. There is such a concept as a” sweet spot”-that is, there is an optimum power level beyond which further gains do not result, no matter how much more energy is fed into the system. In other words, additional power will not necessarily guarantee faster data transfer and higher reliability. Summing everything up, it becomes apparent that future 6G THz wireless networks will actually provide the best of two worlds. By ensuring that the power transmitted, blocklengths, and the distance between devices are properly controlled while energy harvesting is maximally exploited, such networks can provide the

speed necessary to meet the demands of future applications. This will provide not only technical advances but tangible advantages for the end user, whether these be based on smart sensing, immersive virtual environments, or critical communications. In the end, this study seems like the first step towards developing a new generation of networks that have an equal capability when it comes to energy management and information exchange. When moving into a 6G and THz era, this knowledge will prove valuable for engineers, helping them create networks that would be robust, efficient, and forward-looking.

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